Ionic Liquid Ferrofluid Electrospray

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Ionic Liquid Ferrofluid Electrospray Technology

Motivation

An electrostatic field, when applied to the free surface of an electrically conducting liquid, will exert a traction force on the interface that deforms the liquid. This phenomenon, by which electrospray is achieved, has been investigated in depth. It also has been exploited for use in spacecraft propulsion using vacuum-compatible propellants called ionic liquids.[1-7] In electrospray propulsion two characteristics that have significant importance on the performance of the engine are the onset potential and the mass of the emitted particles. At Michigan Tech, a new propellant called an ionic liquid ferrofluid (ILFF) is being investigated for use as an alternative to traditional electrospray propellants. Due to its magnetic susceptibility, the ILFF propellant adds a new variable to the standard electrospray propulsion model.

Goal of Research

The goal of our research is to understand how electric and magnetic fields work together to cause electromagnetic instability in the free surface of an ionic liquid ferrofluid and how this instability impacts the emitted beam of charged particles.

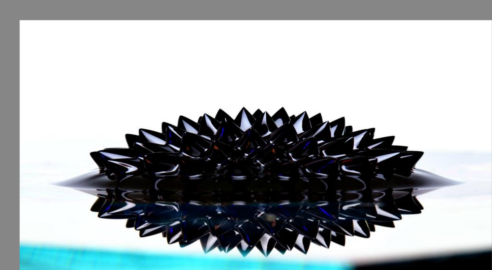
Two aspects of this research are presented here:

1) Mass measurements of particles emitted from and diagnostics of ILFF electrosprays.
2) Modelling the surface instability of a ferrofluid and the onset potential of ILFF electrosprays under combined electric and magnetic fields.

Background

Ferrofluid in a Magnetic Field

Ferrofluids are superparamagnetic liquids. These exotic fluids are composed of nanoscale ferromagnetic particles coated with a surfactant. This surfactant serves to suspend the particles in the carrier liquid. When these fluids are subjected to a magnetic field, the fluid surface deforms into a series of peaks. The shapes of these peaks are dependent on the fluid properties of the ferrofluid and the nature of the applied magnetic field.



Pool of ferrofluid influenced by a magnetic field. Credit: Gregory F. Maxwell

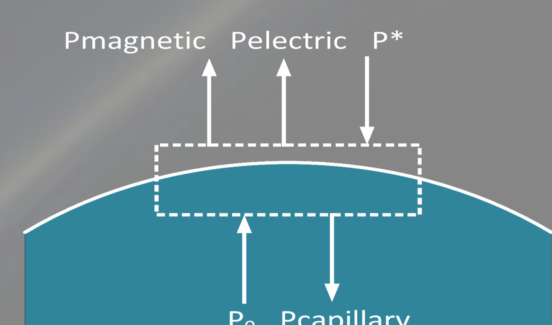
Stress Balance Along a Fluid Interface

Using an augmented Young-Laplace, and assuming a steady state, the equilibrium force balance is derived which includes the new magnetic component.

$$\Delta P + \underbrace{\frac{1}{2}\mu_0(M\cdot\hat{n})^2 + \mu_0\int_0^H M dH}_{\text{Magnetic Terms}} + \underbrace{\frac{1}{2}\varepsilon_0(E\cdot\hat{n})^2}_{\text{Electric Term}} = -\sigma(\nabla_t\cdot\hat{n})$$

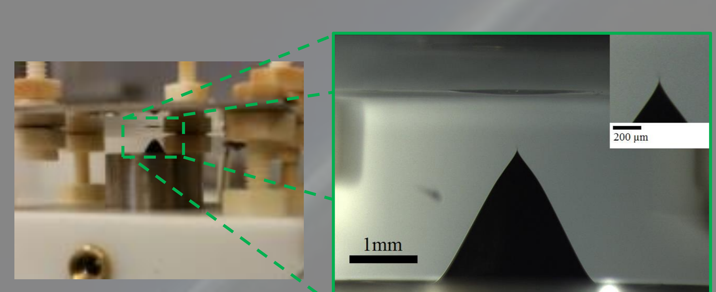
The terms are:

- ΔP – Change in static pressure over the interface
- $\frac{1}{2}\mu_0(M\cdot\hat{n})^2$- Magnetic normal pressure
- $\mu_0\int_0^H M dH$- Fluid magnetic pressure
- $\frac{1}{2}\varepsilon_0(E\cdot\hat{n})^2$ - Electrostatic pressure
- $-\sigma(\nabla_t\cdot\hat{n})$ - Capillary pressure

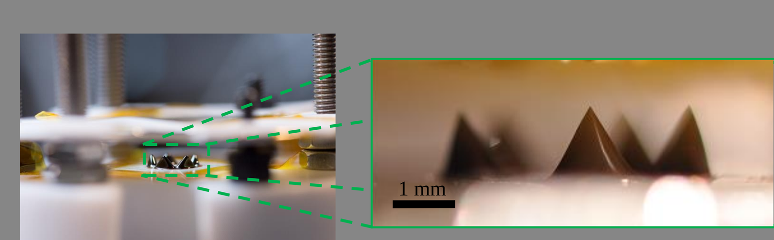


Demonstrated ILFF Electrospray

Prototypes of a "needle-free" single-peak and a five-peak ILFF electrospray emitter have been demonstrated by students in Michigan Tech's Ion Space Propulsion Lab. Images of each of these prototype are shown below.



ILFF single-peak emitter electrospray prototype



ILFF five-peak emitter electrospray prototype

In each of these electrospray studies, visual inspection of the residue from electrospray emission onto the extraction electrode revealed evidence of the magnetic nanoparticles.

Sources

1. Jackson, G.P. and D.C. Duckworth, "Electrospray mass spectrometry of undiluted ionic liquids," Chemical Communications, 0, 2004, pp. 522-523
2. Chiu, Y.H., et al., "Vacuum electrospray ionization study of the ionic liquid, [Emim][Im]," International Journal of Mass Spectrometry, 265, 2007, pp. 146-158
3. Lozano, P.C., "Studies on the Ion-Droplet Mixed Regime in Colloid Thrusters," Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, 2003
4. Prince, B.D., B.A. Fritz, and Y.-H. Chiu, Ionic Liquids in Electrospray Propulsion Systems, in Ionic Liquids: Science and Applications2012, American Chemical Society. p. 27-49.5.5
5. Lozano, P. and M. Martínez-Sánchez, "On the dynamic response of externally wetted ionic liquid ion sources," Journal of Physics D: Applied Physics, 38, 2005, pp. 2371
6. Lozano, P. and M. Martínez-Sánchez, "Ionic liquid ion sources: suppression of electrochemical reactions using voltage alternation," Journal of Colloid and Interface Science, 280, 2004, pp. 149-154
7. Chiu, Y.-H., et al., "Mass Spectrometric Analysis of Ion Emission for Selected Colloid Thruster Fuels," 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Huntsville, Alabama

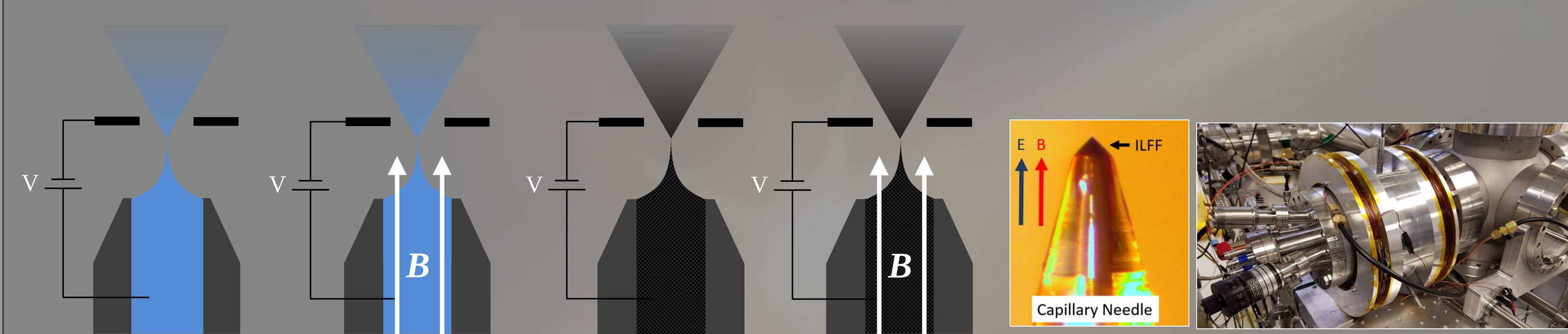
Mass Measurements and Electrospray Diagnostics

Goal of Study

The goal of this study was to determine how the presence of magnetic nanoparticles suspended in an IL affect the resulting electrospray emission when compared with neat IL electrospray; and how the application of a magnetic field affects emission of newly formed IL colloid electrospray.

Experimental Apparatus and Setup

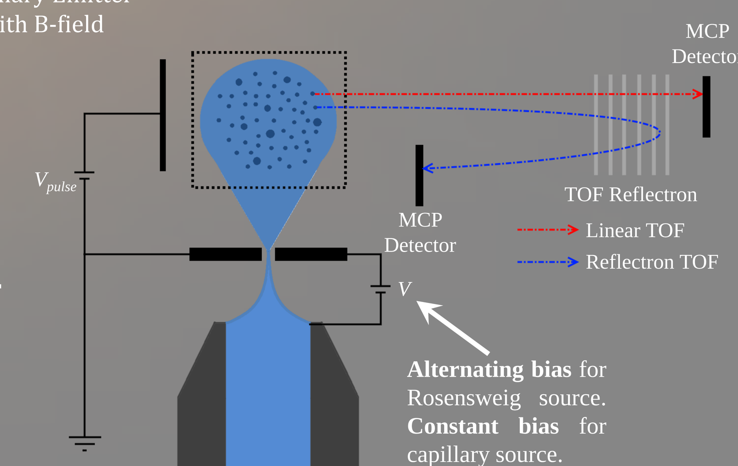
A pressure-fed capillary system was designed and built for experimental testing of ILFF electrospray (shown below). Emission current and minimum flowrate were measured for the four sources; the propellant of the sources was neat IL and five different concentrations of ILFF.



Ionic Liquid Capillary Emitter | Ionic Liquid Capillary Emitter with B-field | Ionic Liquid Ferrofluid Capillary Emitter | Ionic Liquid Ferrofluid Capillary Emitter with B-field | Operating ILFF Capillary Source | Helmholtz Coil on Vacuum Facility

A time-of-flight mass spectrometer (TOF-MS) was used to measure the mass of particles within the beam. This is made possible by measuring the flight time of charged particles and using the relationship between kinetic and electric energies of the particles.

$$\frac{1}{2}mu^2 = qeV \longrightarrow \frac{m}{q} = \frac{L_{Tof}^2}{t_{flight}^2 2V}$$

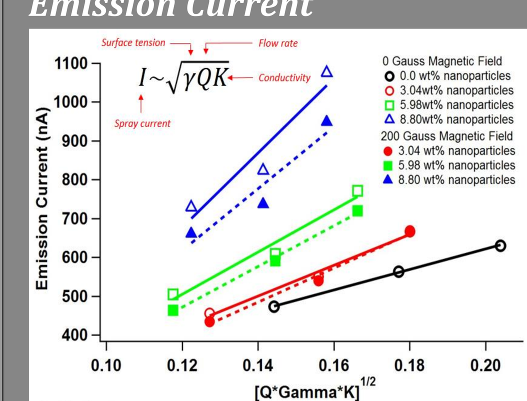


Alternating bias for Rosensweig source. **Constant bias** for capillary source.

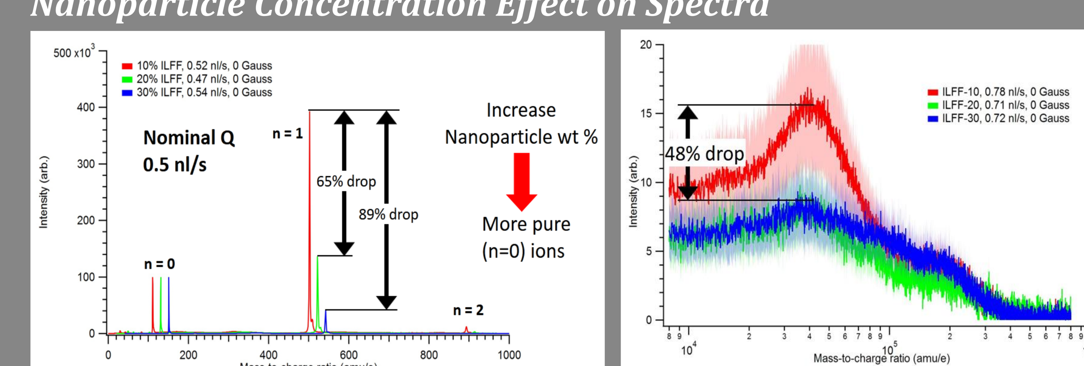
Results

Electrospray diagnostics for the four electrospray sources were measured, these include emission current and minimum flowrate. Mass spectra of the four electrospray sources were also collected. The results are shown below.

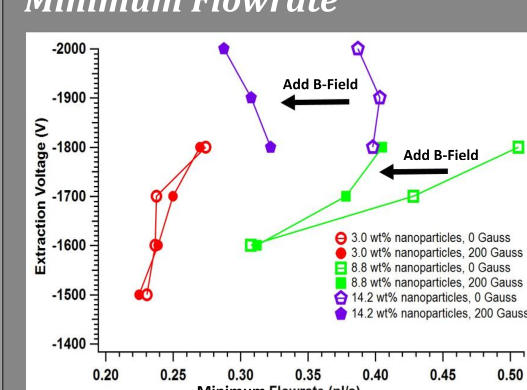
Emission Current



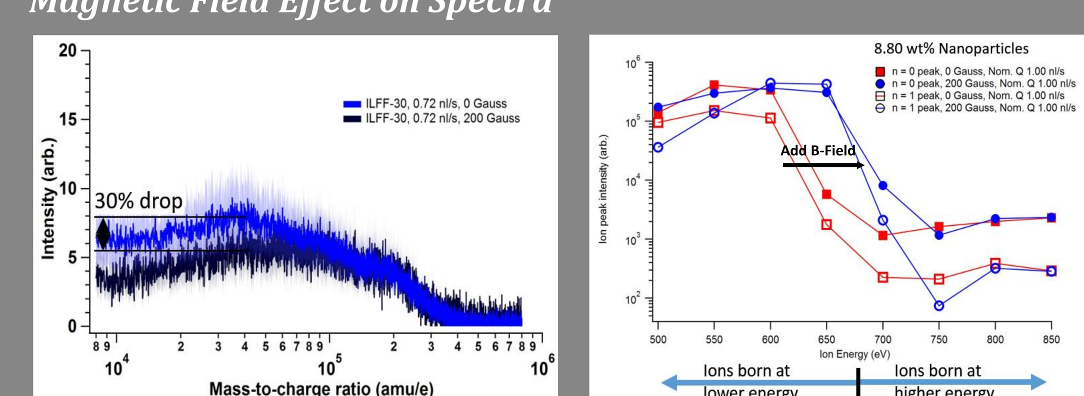
Nanoparticle Concentration Effect on Spectra



Minimum Flowrate



Magnetic Field Effect on Spectra



Conclusion

The addition of nanoparticles to a ionic liquid propellant was shown to be a significant variable in the emission current, the minimum operable flowrate, and the emitted masses. Subjecting the new colloid propellant to a magnetic field was found to greatly affect the operation of the electrospray (flowrate and emission current), however the effect on the emitted masses was relatively small unless high concentrations of nanoparticles were used.

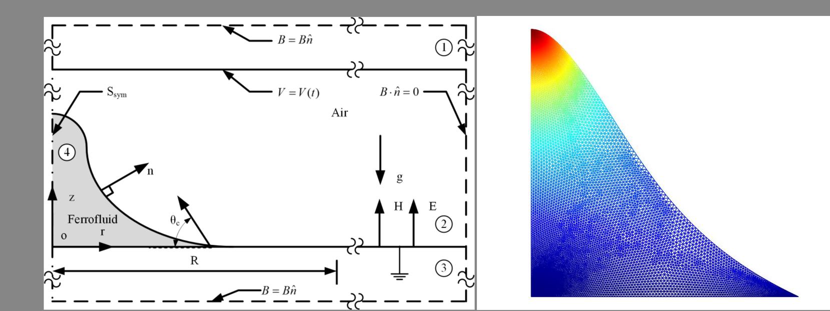
Peak Geometry and Electrospray Onset Numerical Modeling

Goal of Study

One goal of this study was to numerically simulate the steady-state behavior of a droplet of a conductive ferrofluid in the presence of electric and magnetic fields. A second goal was to numerically simulate the onset potential of an ILFF electrospray. To validate the accuracy of the numerical simulation, results were compared against images of the ferrofluid meniscus under matching field conditions, and empirical results from the ILFF electrospray source.

COMSOL Model

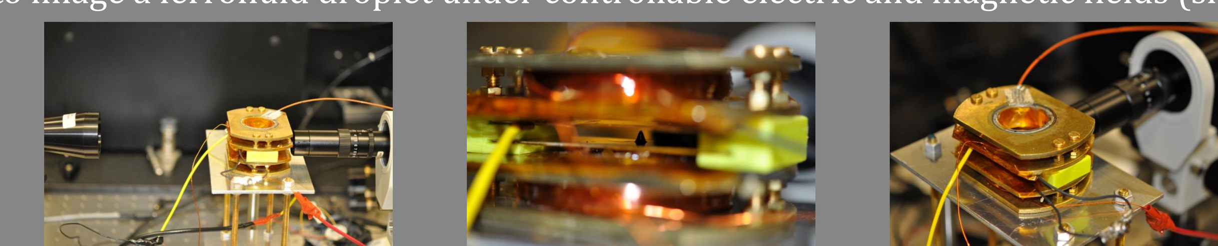
The simulation domain utilized for the peak geometry investigation is shown here; a similar domain was used for the onset potential investigation, however a capillary needle geometry was added to pin the outer edge of the droplet. Interfaces used in the Model: 1) Two Phase Flow – Moving Mesh 2) Electrostatics 3) Magnetostatics



(Left) Simulation domain for single ferrofluid droplet subject to a vertical magnetic and electric field. (Right) Sample mesh for fluid domain.

Experimental Setup

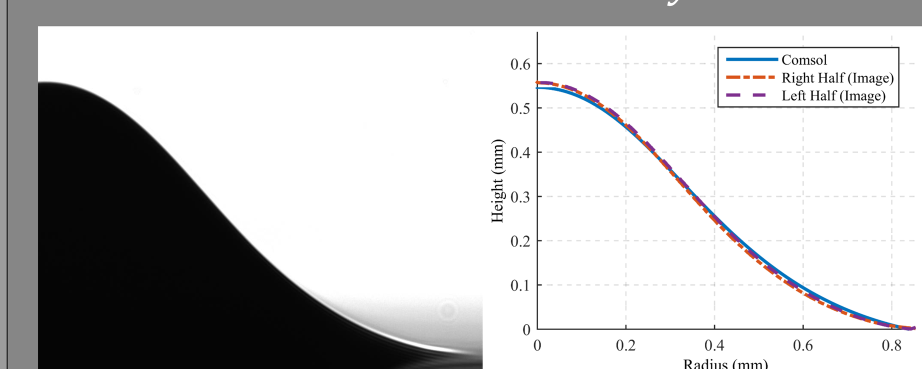
To determine the accuracy of the numerical model of peak geometry, an imaging apparatus was utilized to image a ferrofluid droplet under controllable electric and magnetic fields (shown below).



To determine accuracy of numerical model of onset potential, the onset potentials for a pressure-fed ILFF electrospray source were measured while a Helmholtz coil applied a variable magnetic field to the emitter (shown in center column).

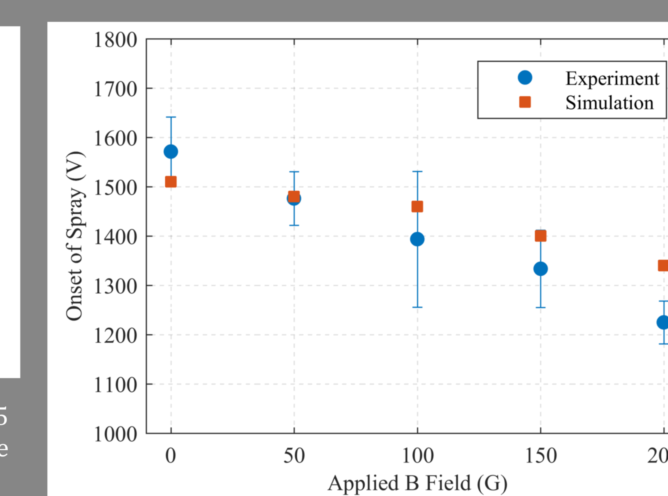
Results

Simulation Validation – Peak Geometry



(Left) Fluid droplet with a volume of 0.3353 mm^3 magnetic field of 237.5 Gauss. (Right) COMSOL solution of a fluid droplet of equivalent volume exposed to the same field strength.

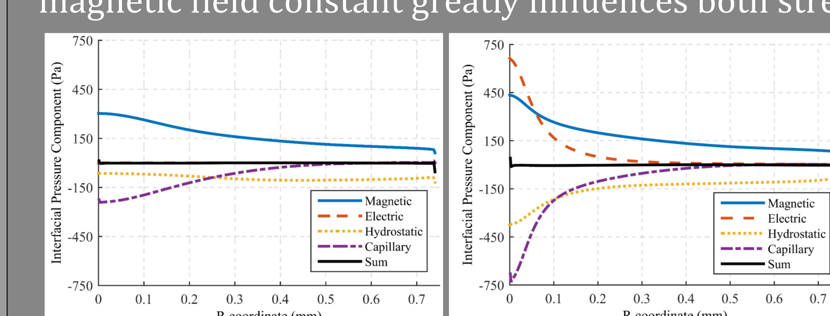
Simulation Validation - Onset Potential



Onset Potentials as a function of applied magnetic field from COMSOL model and empirical measurements.

Field Influence on Pressures

Since the magnetic and electric fields act in tandem, the addition of an electric field while holding the magnetic field constant greatly influences both stresses.



(Left) Pressure plot for a fluid droplet in a 210 G magnetic field with no electric field. (Right) Pressure plot for the same fluid droplet exposed to the same magnetic field an applied voltage of 2500 V.

Conclusion and Future Work

The high-level of agreement between the numerical model and empirical data demonstrates that FEA methods can be accurately used to model the ferrofluid meniscus under electric and magnetic fields, including the influence of magnetic stresses on the onset of emission behavior of electrospray . This will enable further research in the modeling of magnetic fluids under combined electric and magnetic fields to be perused.

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